Hadronic Dark Matter Searches at CMS at $\sqrt{s} = 13$ TeV

Subtitle

By

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A dissertation submitted to the University of Bristol in accordance with the requirements for award of the degree of Doctor of Philosophy in the Faculty of Science.

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Word count: number in words

Abstract

Here goes the abstract

Dedication and acknowledgements

Here goes the dedication.

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: ..... DATE: .....

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Chapter 1

Introduction

Begins a chapter. Example: When the beloved cellist (Christopher Walken - outstanding) of a world-renowned string quartet receives a life-changing diagnosis, the group's future suddenly hangs in the balance: suppressed emotions, competing egos and uncontrollable passions threaten to derail years of friendship and collaboration. Featuring a brilliant ensemble cast (including Philip Seymour Hoffman, Catherine Keener and Mark Ivanir as the three other quartet members), it is a fascinating look into the world of working musicians, and an elegant homage to chamber music and the cultural world of New York. The music, of course, is ravishing (the score is the work of regular David Lynch collaborator Angelo Badalamenti): A Late Quartet hits all the right notes.

1.1 Section

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1.1.1 Subsection

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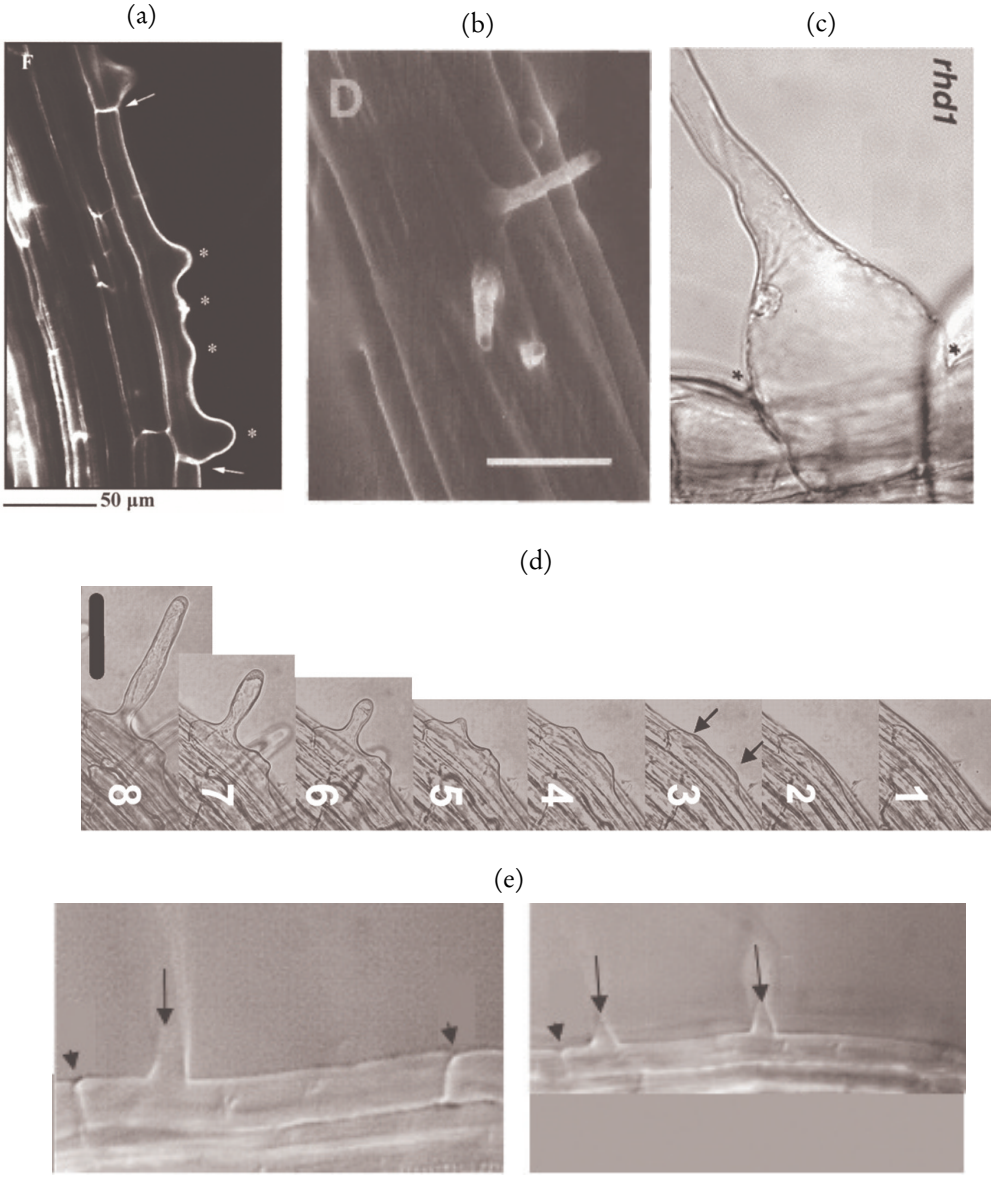

FIGURE 1.1. (a) A mutant RH cell. Asterisks show multiple sites of RH initiation in a single root hair cell (indicated by the arrows). Figure reproduced from [?]. (b) Hair-forming cell with three RH initiation locations. The bar represents $50\mu m$. Figure reproduced from [?]. (c) Large bump in mutant *rhd1*. Figure reproduced from [?]. (d) Mutant overexpressing gene *ROP2*; from right-hand to left-hand, numbers indicate progressive snapshots at different times. RH initiation sites are indicated by the arrows. The bar represents $75\mu m$. Figure reproduced from [?]. (e) Mutants affected by auxin. On the left-hand side, RH site is farther away from the apical end (left arrow cap); on the right-hand side, multiple RH locations (arrows). Figure reproduced from [?].

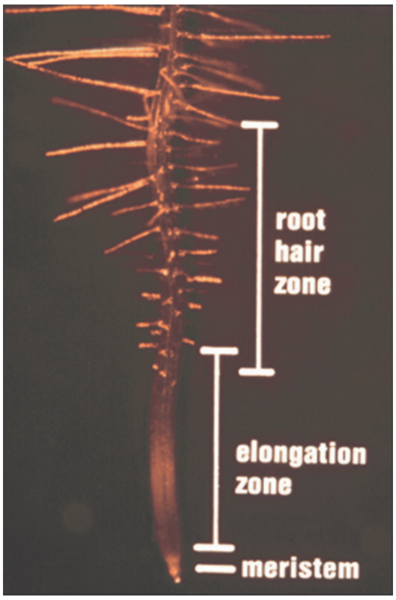

FIGURE 1.2. Developmental zones of an Arabidopsis root. Figure reproduced from [?].

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Doing the same to check both sides of the paper (for when it's bound).

Also testing glossaries: latex, Large Hadron Collider, LHC, Large Hadron Collider (LHC).

Also testing references: [5] (article), [8] (book), [7] (inproceedings), [4] (techreport).

Testing numbers: 1234567890

Testing alphabet: The quick brown fox jumps over the sleazy dog

Testing equations:

$$B(P) = \frac{\mu_0}{4\pi} \int \frac{I \times \hat{r}}{\bar{r}^2} dr \tag{1.1}$$

Chapter 2

Theory

This is the theory chapter.

- Give an overview of the fundamental forces and particles.
- Discuss the Standard Model in detail, emphasising certain aspects as they relate to dark matter and the Higgs field (and boson).
- Discuss the theory behind combined Higgs to inv.: only SM process in which Higgs decays invisibly is $H \to ZZ \to 4\nu$ with branching ratio of 0.1 % [6], whilst the current observed experimental limit is 19 % from CMS [9] and 26 % from ATLAS [1]. If new, invisible particles couple to Higgs, branching ratio will be enhanced.
- Discuss the theory behind the semi-visible jets analysis (main sources from Refs. [2], [3]): strongly interacting dark sector in Hidden Valley scenario with a portal to the visible sector. Mentioning dark quarks, dark confinement scale, dark hadronisation and decay, running coupling, etc.
- Explain some of the phenomenological/experimental event characteristics that overlap with both analyses, i.e., what a jet is, and maybe energy sums like $p_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, $H_{\mathrm{T}}^{\mathrm{miss}}$, etc.

Chapter 3

The LHC and the CMS experiment

This is the detector chapter.

- Explain CERN and the LHC in more detail.
- Give an overview of the CMS experiment and detector (including all subsystems, object identification, algorithms for event/object reconstruction like Particle Flow and anti-k_T algorithm, and algorithms for tagging objects like *b*-jets).
- Either as a subsection in this chapter or in a separate chapter, discuss the Level-1 Trigger in depth. Emphasise the jet and energy sum triggers as I've worked on them, and Calorimeter Layer-2 for the same reason.

Chapter 4

Combined search for the invisible decay of the Higgs boson in hadronic channels

This is the analysis chapter on $H \rightarrow$ inv..

- Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.
- Discuss the necessity of including all production modes of Higgs (invisible final state, so characterise events based on initial/additional particles). Also mention how sensitive each production mode is at contributing to the branching ratio limit. Emphasise the non-VBF modes (ggF, ttH, WH, ZH) in this chapter as that's what I've been working on and another student will be covering VBF.
- Talk about what makes this analysis unique: doing a combination over all production modes from the start instead of separate analyses combined at the end. Means we can share samples, systematics, background methods and workflows, build in orthogonality between the different modes and cover as much phase space as possible (with new final states such as boosted Z bosons with unresolved subjets). This makes the analysis much more cohesive and consistent.
- Include object definitions, overall analysis strategy, triggers, signal production (with each non-VBF mode in detail), event selection, background estimation and results/limit (including comparisons to previous results).
- Emphasise my contributions: control region construction and studies, background estimation, and other studies I will have conducted by the time I write up.

- Current material: no public plots as of yet. Hope to finish analysis by the time I begin writing up. We are preparing a CMS internal analysis note, documenting all aspects of the analysis. I will add all relevant information there which I can subsequently use when writing this chapter.

CHAPTER 5

SEARCH FOR DARK MATTER THROUGH THE PRODUCTION OF SEMI-VISIBLE JETS

This is the analysis chapter on semi-visible jets.

– Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.

– Include object definitions, triggers, overall analysis strategy, signal production, event selection, background estimation and results/limit (including comparisons to similar searches – monojet/dijet exotic searches).

– Emphasise my contributions: *s*- and *t*-channel signal model production and understanding. Angular variable study for QCD background rejection (if used).

– Current material: no public plots as of yet. Hope to finish *s*-channel analysis soon (see previous section for caveats regarding inclusion), no timeline on *t*-channel analysis.

CHAPTER 6

CONCLUSIONS

This is the conclusion.

- Include a summary of thesis and work done over the course of my PhD with emphasis on the most important results/contributions.
- Mention the direction the semi-visible jet and Higgs to invisible analyses can take (sharing ideas/strategies I have, potential improvements with more LHC data and future prospects from potential future experiments).

Appendix A

Begins an appendix

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Glossary

anti-k_T algorithm .

latex Is a mark up language specially suited for scientific documents.

semi-visible jet .

Acronyms

ATLAS A Toroidal LHC ApparatuS.

CERN Organisation Européenne pour la Recherche Nucléaire/European Organization for Nuclear Research.

CMS Compact Muon Solenoid.

LHC Large Hadron Collider.

QCD Quantum Chromodynamics.

SM Standard Model.

VBF vector boson fusion.